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Laboratory measurements

of complex resistivity characteristics of oil shales

from Saterdal #1 corehole,

Piceance Creek Basin, Colorado

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Abstract: Laboratory measurements of the complex electrical resistivity
characteristics of more than 120 oil shale samples from Saterdal #1
corehole, Piceance Creek Basin, Colorado, indicate the following:
(1) The presence of kerogen in wet Green River Formation marls increases
their d.c. resistivities from about 300 ohm-m to more than 10^5 ohm-m,
makes them isotropic, and causes a substantial frequency dependence.
(2) Microanisotropy coefficient increases with water content from about
2 to as much as 200. The effect seems to be due to an extreme porosity
and/or permeability anisotropy, involving a drop in longitudinal
resistivity from about 10^8 ohm-m for dry samples to as low as 10^5 ohm-m
for wet ones, while transverse resistivities stay relatively constant
at about 10^8 ohm-m. (3) Intermediate grade oil shales show the most
extreme anisotropy effect; both very rich and very lean oil shales are
more nearly isotropic. (4) Both wet and dry oil shales show a pronounced
frequency effect for frequencies >10Hz, and may make good IP targets.

Campbell (1977) reports that surface d.c. electrical soundings in

the Piceance Creek Basin, Colorado, show that oil shales there have a

net anisotropy coefficient of 9 or more, among the highest such values

ever reported for a geologic material. This high net anisotropy results

from the combination of a macroanisotropy component due to thin,

saline-water bearing, conducting horizons within the high-resistivity

oil shale sequence, and a microanisotropy component due to kerogen

layering within the oil shale itself.

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In order to investigate the macroanisotropy of oil shales, laboratory measurements were made of the electrical properties of samples of typical core from 36 different depths in Saterdal #1 well, Piceance Creek Basin, Colorado (Figure 1). The samples included oil shales with a wide range of Fisher assays (indicated on the figure), as well as samples of the commonly-present evaporite minerals nacholite, dawsonite, and halite.

The samples which were measured consisted of an approximately 0.4 cm-thick slice from the top, bottom, and 2 faces of a 5 cm length of quarter split 4-inch (10 cm) diameter core from each of the 36 depths sampled in the well. Each depth therefore yielded two T (transverse) samples, from depths a few inches apart, on which to measure resistivity transverse to the thin kerogen layering; and two L (longitudinal) samples, at right angles, on which to measure the resistivity longitudinal to this layering. Each sample identification number indicates the depth in feet[*] from which it came in the well and its L or T character: sample 1165T2 for example, is the second of the two transverse samples from depth 1165.

Most samples were measured both dry and wet. "Dry" means that the sample was subjected to 24 hours of vacuum drying to remove all pore water and adsorbed moisture. "Wet" means that the sample was soaked for a week in distilled water, including 24 hours under sufficient vacuum to bubble out the gases, but not boil off the water bath. (This treatment dissolved some of the evaporites, and so their wet resistivities

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* 1 foot = 0.3048 meter

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were not measured.) During the soaking period, the resistivity of a 150 ml water bath containing the 4 samples from a given depth dropped from 3000 ohm-m to the order of 100 ohm-m, for oil shale samples. The samples were measured in three-electrode sample holders about 2.5 cm in radius. Measurements were made at (at least) 4 frequencies--1 KHz, 10 KHz, 100 KHz, and 1 MHz--using apparatus and an automated procedure described by Olhoeft (written commun., 1977). Figures 2, 3, 4, and 6 show log-log plots of the real component (only) of complex resistivity for selected samples. Experimental values are shown and d.c. resistivity values are indicated by a symbol and bar pointing to the left side of the graph. These d.c. values were derived from 1 KHz to 1 MHz measurements, by subtracting the dielectric contribution, and represent minimum values for they assume no additional low-frequency relaxation mechanisms. True d.c. measurements--done as spot-checks on about 5% of the samples--are usually about half an order of magnitude above the derived values. The solid lines connecting the data points are sketched in to represent a simple curve, of several possible ones, between the lowest frequency measurement and d.c. values. Some of the charts show data points as low as 10 Hz that were taken with the use of a manually-balanced bridge. Often, however, measurements over the lower frequency decades failed certain consistency checks at these frequencies. More reliable results at low frequencies await changed sample configuration, four-electrode sample holders, and a better controlled environment.

Resistivity values shown on Figures 2, 3, 4, and 6 are uncorrected for density of the samples. Some trial density corrections were done

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on a few dry samples of oil shale, and it was found for these samples
that dielectric constant, K, varies with density, ρ, as

$$K = (2.3 \pm 0.1)^\rho.$$

In those cases where it was tried, applying the density correction
reduced the scatter between the 2 L and between the 2 T values derived
for d.c. resistivity for samples from a given depth.

Figure 2 shows the difference between wet and dry oil shale. Dry
oil shale has a frequency dependence involving a slope of about -1 on
the log-log plot. (A Debye material--one with a single relaxation
mechanism--would have a -2 slope on this same chart.) There probably
is no substantial difference at high frequencies between L and T
components. At low frequencies L and T components separated, and at
d.c. (zero frequency) the current flows easier longitudinal to the
bedding rather than transverse to it by about a factor of 2. For wet
oil shale the T curve is little altered: the d.c. resistivity drops
by a factor of about 5 and the frequency-dependent segment shifts
somewhat to the right. The L component, on the other hand, is
radically different when the sample is wet: the curve rotates down and
may become almost flat. For this particular sample, the most extreme
of those measured, the d.c. resistivity dropped by over four orders of
magnitude, while the frequency effect disappeared at low frequencies
and greatly diminished at high ones. The d.c. microanisotropy
coefficient is the square root of the ratio of the d-c T value to that
of the L value, here in excess of 100. We conclude that adding water
to oil shale decreases the d.c. resistivity, increases its
microanisotropy, and tends to diminish the frequency effect.

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Figures 3a and 3b show the effect of adding thin kerogen layering to wet marl to make oil shale. Figure 3a shows the real resistivity of wet marl to be about 300 ohm-m, and fairly independent of frequency. Marl is isotropic, with equal T and L resistivities. Figure 3b shows a typical wet oil shale, consisting of marl plus kerogen layering. The d.c. resistivity is greater than that of wet marl by about four orders of magnitude. As does all dry oil shale, this wet sample shows a log-log slope of approximately -1 at high frequencies; a possible IP response for oil shale, wet or dry, may be indicated. Again, microanistropy is evident; the d-c T and L resistivities differ by a factor of about 10.

Figures 4a, 4b, 4c, and 4d show real resistivity curves for four different grades of oil shale--10, 22, 40, and 56 GPT (gallons per ton).[*] The 10 GPT sample is essentially isotropic. Through the first three grades, there is a trend of increasing T values, decreasing L values; in other words, increasing microanisotropy. As d.c. resistivity for L decreases, the frequency-dependent portion of the curve shifts right. At the same time, a substantial difference appears between curves for the two nominally-identical L-sample slices. Since the two L slices came off right-angle faces of quarter-split core, a 3-dimensional anisotropy may be indicated.

As noted, oil shale has a varve-like structure consisting of minilayers of kerogen, interspersed with minilayers of marl. Lean oil shales like the 10 GPT sample seem not to have enough kerogen to make

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* 1 GPT = 4.173 liter/metric ton

continuous layers--presumably the tiny pancake-shaped blotches of kerogen provide little impediment to either L or T current flow in the marl groundmass. As kerogen content increases to 22 GPT and to 40 GPT the resistive layers become more continuous. The result is a barrier to transverse current, but a conduit for longitudinal current along the remaining marl horizons. At 56 GPT, the kerogen content is sufficiently high that the layering is no longer readily distinguished in hand specimen. The sample is kerogen-saturated; the marl conduits are being sealed off, and the trend is back to isotropy. Hence, the seeming paradox--only middle-grade oil shales are highly anisotropic. The very rich and very lean oil shales have similar electrical properties.

To check the above implication that the middle-grade oil shales may have a well-developed longitudinal porosity, porosity measurements were made on sample 2234L1 using a mercury porosimeter. Figure 5, a graph of the results, shows that almost all of the sample's pores are 27 microns in diameter. Narrow porosity bands like this are typical of commerically-prepared filters, but are highly unusual for natural materials. This result may have an important bearing on the diagenesis of oil shales.

Figures 6 shows real resistivities for the evaporite salts halite, dawsonite, and nahcolite. The curves are for dry L sections. (T curves are similar.) The derived d.c. resistivities are higher than those for oil shale, and a frequency effect with about -1 slope is seen at the measured frequencies.

Table 1 gives measured dielectric constant K and loss tangent D at 1 MHz for typical samples. The generally low values of D, less than 0.1, indicate oil shale to be quite transparent to radar waves. In oil shale mining operations, therefore, it appears that radar could be used effectively to locate water-or-clay-bearing bad ground ahead of an advancing mine opening.

References cited

Campbell, D. L., 1977, Electrical soundings near Yellow Creek, Rio Blanco County, Colorado: Jour. Research U.S. Geol. Survey, vol. 5, no. 2, p. 193-205.

Table 1.--Dielectric constant K and loss tangent D at 1 MHz frequency

for selected samples.

Sample			K	D
787	T1*	Wet marl	40.47	1.5647
	T2*		36.07	1.4491
	L1*		52.21	1.5901
	L2*		44.81	1.4308
1150	T1*	Wet 10GPT oil shale	6.464	0.0693
	T2*		5.631	0.0856
	L1*		7.304	0.1366
	L2*		7.216	0.1274
1098	T1*	Wet 22GPT oil shale	5.609	0.0545
	T2*		4.964	0.0639
	L1		6.620	0.1184
	L2		1.377	0.0109
2234	T1	Wet 40GPT oil shale	4.657	0.0244
	T2		4.716	0.0280
	L1		5.234	0.0552
	L2		6.112	0.4731
1165	T1*	Wet 56GPT oil shale	4.847	0.0838
	T2*		5.186	0.0876
	L1*		7.092	0.1690
	L2*		6.965	0.1525
1198	T1	Dry dawsonite	5.325	0.0031
	T2		5.364	0.0014
	L1		5.086	0.0030
	L2		5.262	0.0026
1615	T1	Dry halite	5.016	0.0330
	T2		7.316	0.1010
	L1		5.955	0.0290
	L2		5.989	0.0409

* Measurement at 0.5 MHz
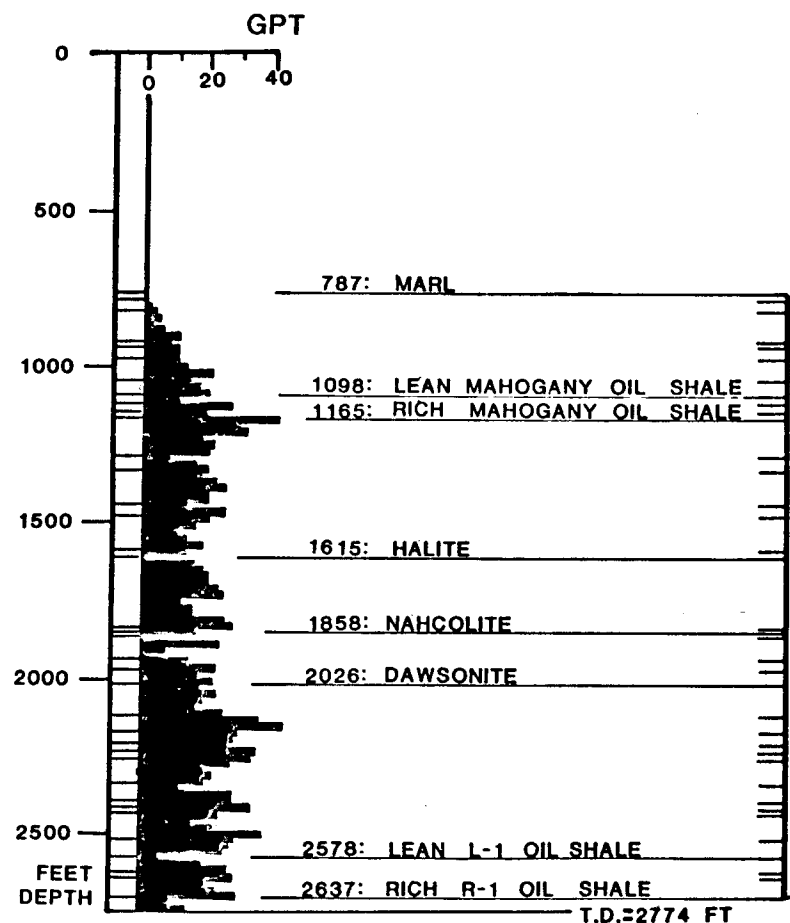
a.
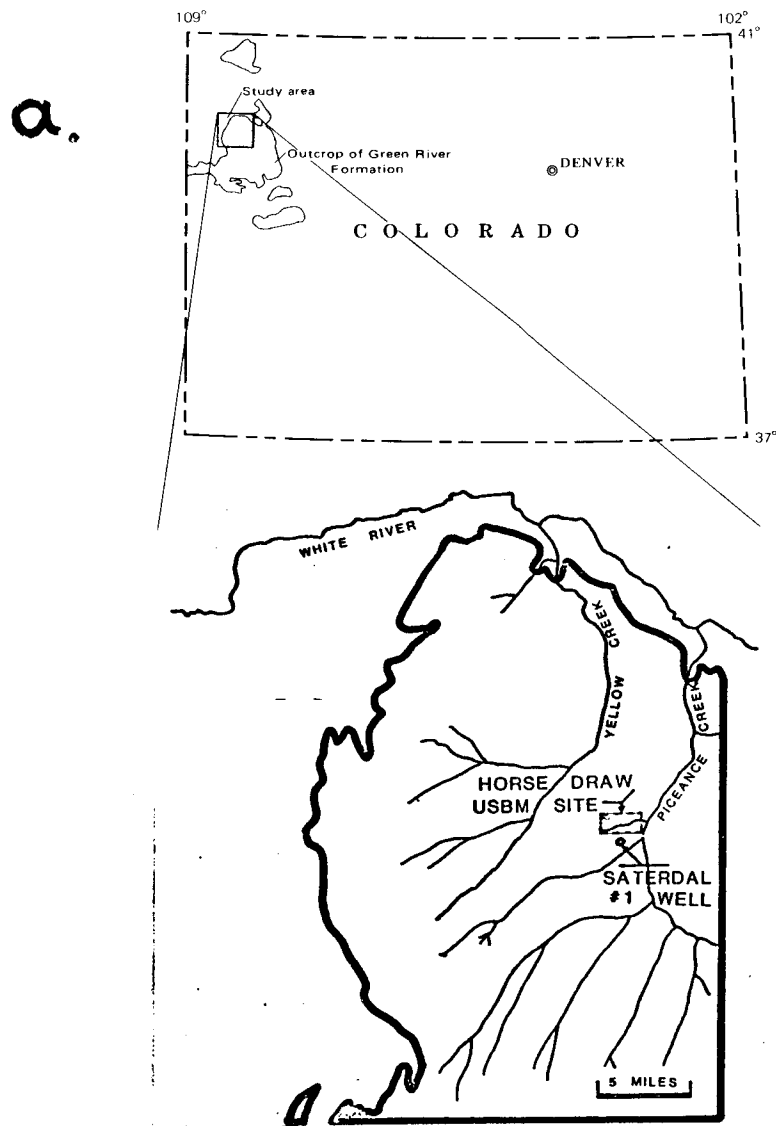
SATERDAL # 1

b.

Figure 1.--(a) Location map of Saterdal #1 corehole. (b) Depths in Saterdal #1 well from which samples were taken, indicated by horizontal bars. Samples were given an identification number corresponding to the depth in feet, indicated here, from which they originated. Fisher assays in GPT (gallon per ton) of shale oil are shown, averaged over 20 ft (6 m) intervals. However, assays reported in text are averages over a smaller, 2 ft (0.6 m), interval which included the sample.
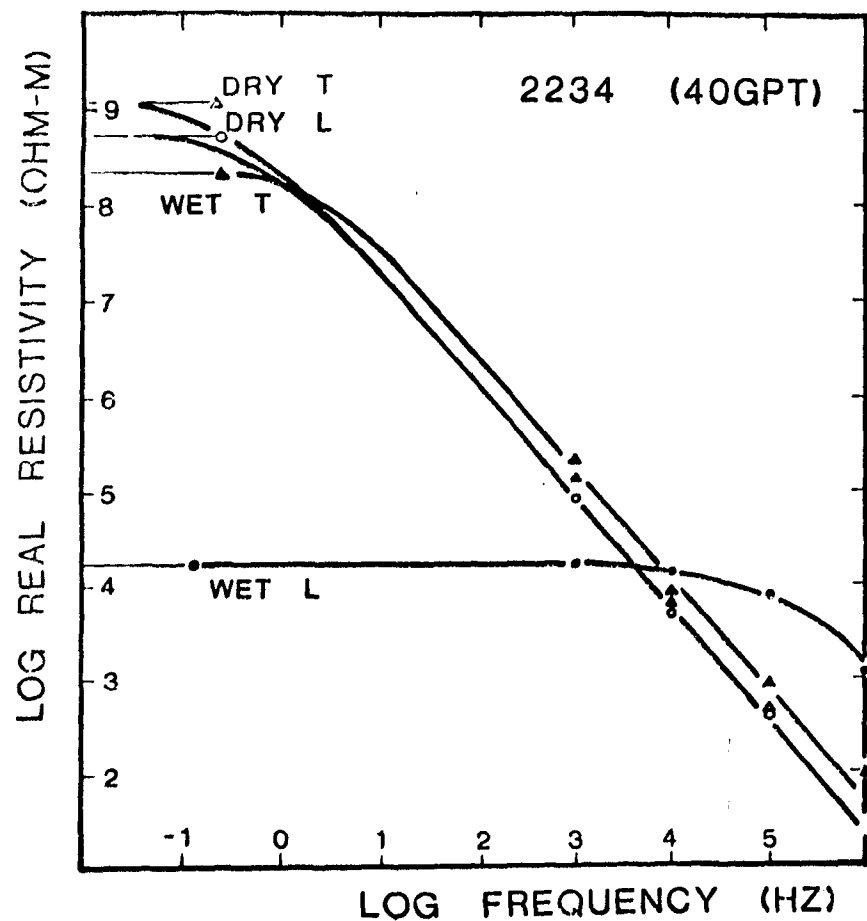
Figure 2.—Log-log plot of real component of resistivity versus frequency for wet and dry oil shale. All dry samples and wet transverse (T) samples of oil shale show similar properties, but wet longitudinal (L) samples can be very different, as in the extreme case shown here. The effect is probably due to a strongly aligned longitudinal porosity in the oil shales.
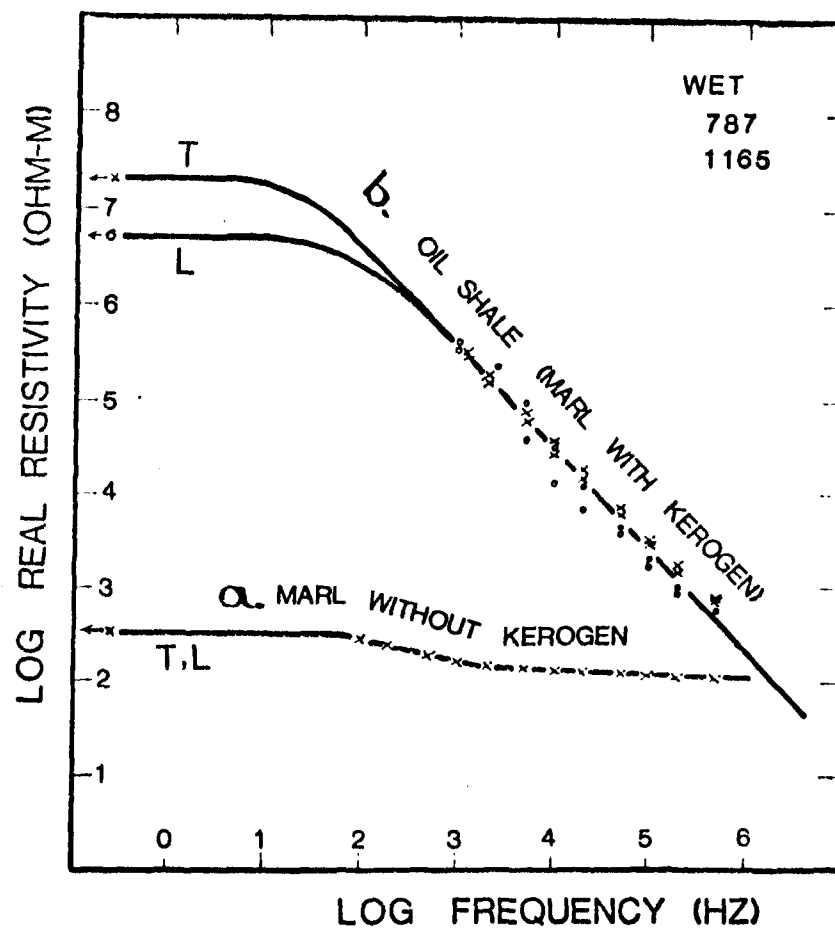
Figure 3.—(a) Resistivity-frequency plot for wet marl, showing relatively low resistivity and frequency effect. (b) Similar plot for oil shale, showing high d.c. resistivity, anisotropy, and frequency effect.
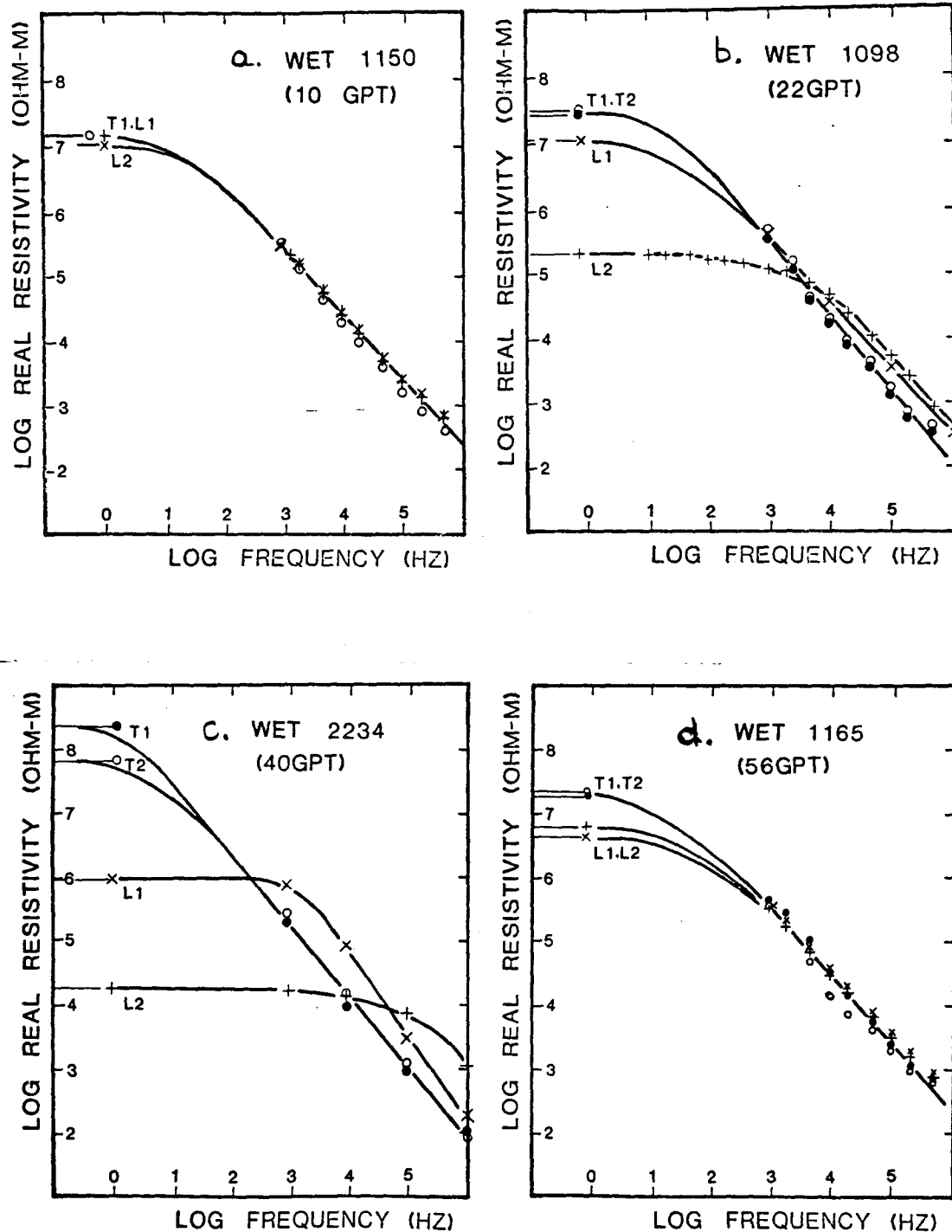
Figure 4.--Log-log plots of real resistivity versus frequency for four grades of oil shale: (a) 10 GPT, (b) 22 GPT, (c) 40 GPT, and (d) 56 GPT. Only the middle-grades, for which the marl-kerogen banding is most pronounced, show extreme anisotropies.

EACH VEFT INC IS 5% CUM POROSITY= 4.458E-04   CC/GM
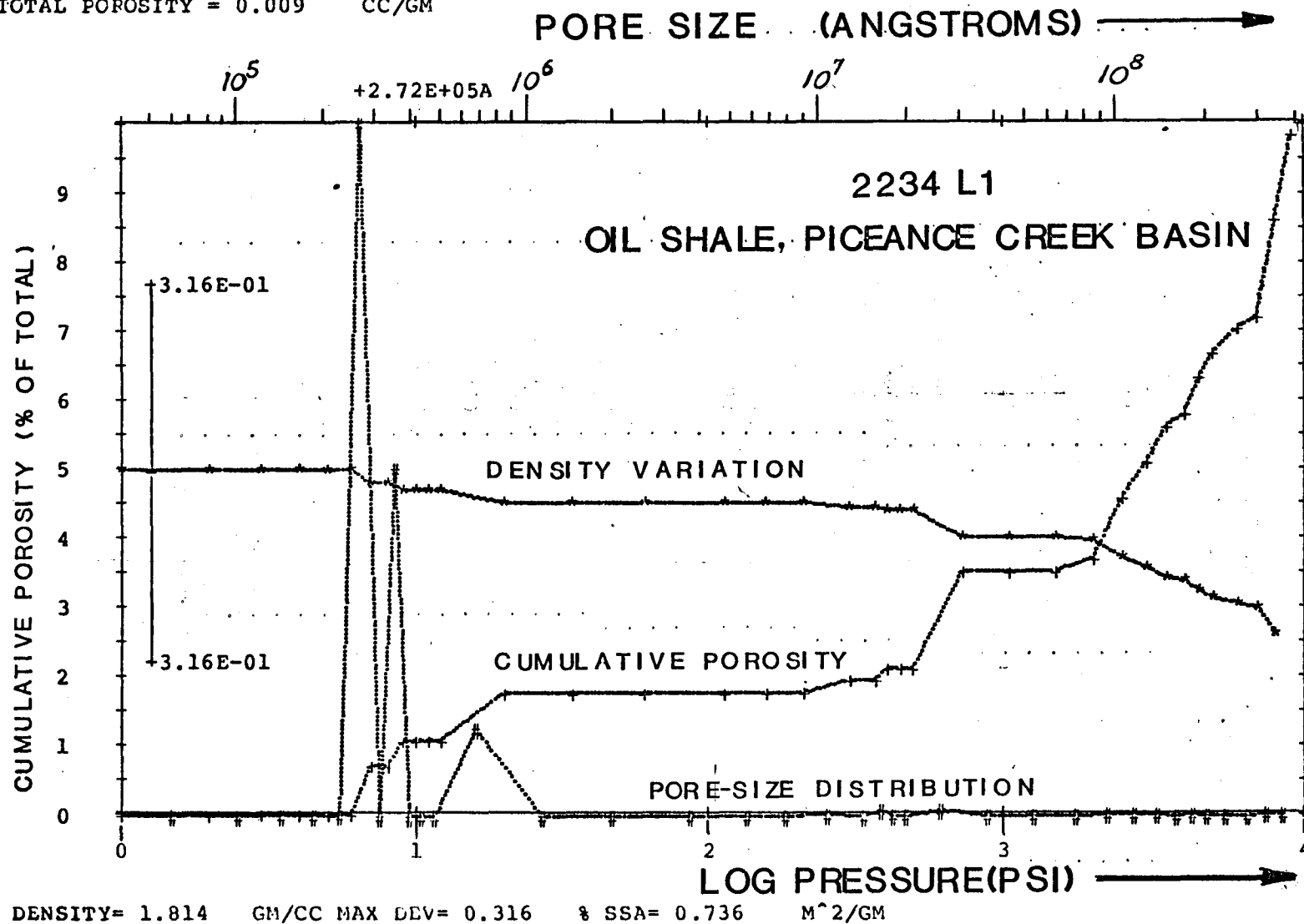TOTAL POROSITY = 0.009   CC/GM

Figure 5.--Graph showing density variation (* signs), cumulative porosity (+ signs), and pore-size distribution (# signs) versus log pressure in psi for a mercury porosimeter run on oil shale sample 2234L1. 1 psi = 0.069 bar. Practically all of the pores have a diameter of 2.7 x 10^5 angstroms = 27 microns.
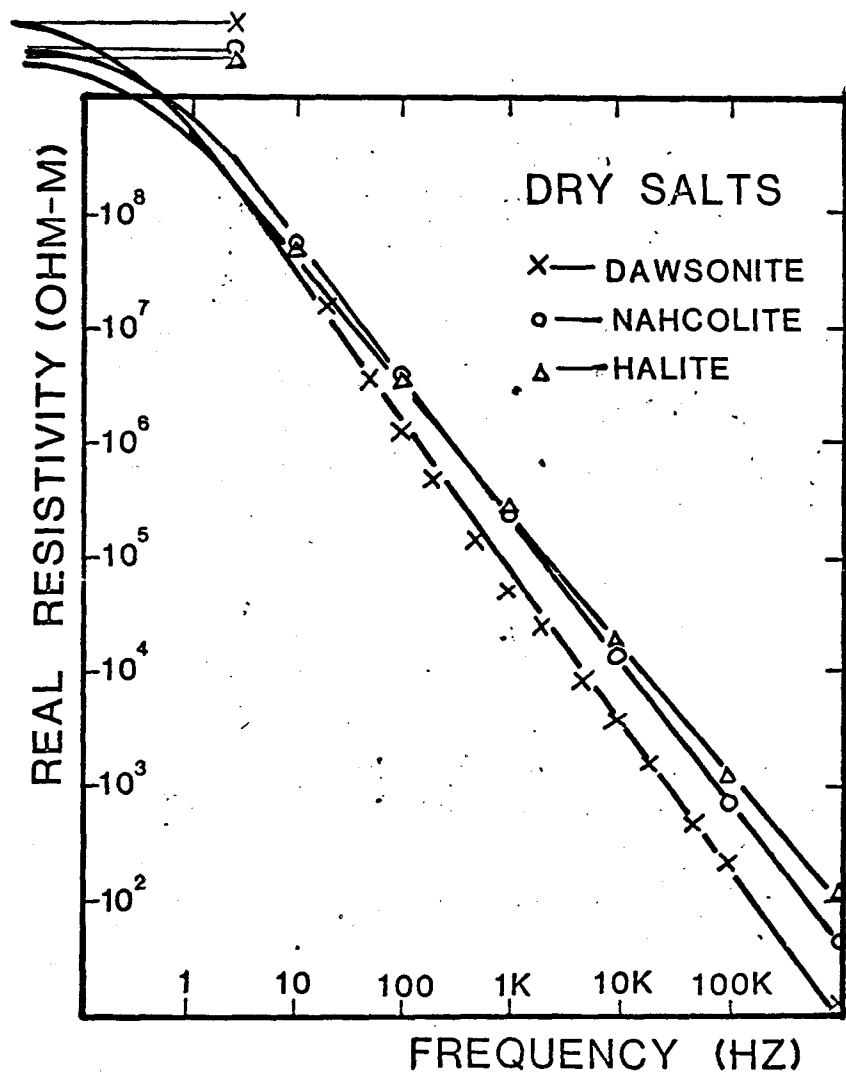
Figure 6.--Log-log plots of real resistivity versus frequency for dry samples of the evaporite salts dawsonite, nahcolite, and halite.
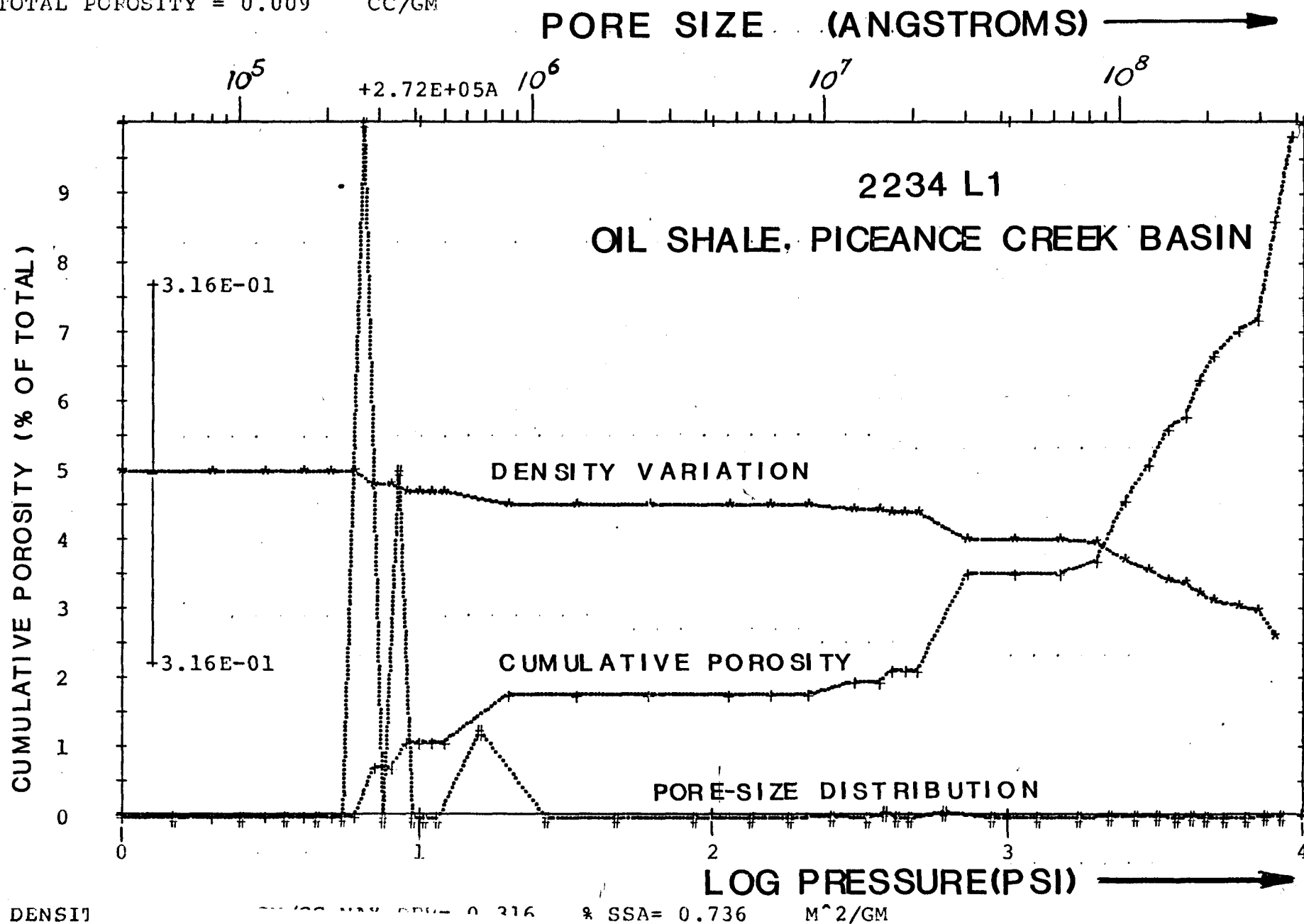
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